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G.R. Brooks

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Abstract

The thicknesses of 537 and 387 rhythmic couplets were measured along composite sequences of glacial Lake Ojibway glaciolacustrine deposits recovered in cores from Duparquet and Dufresnoy lakes, Quebec, respectively. The couplets span varve numbers 1137 to 1742 (Lac Duparquet) and 1189 to 1625 (Lac Dufresnoy) with respect to the Timiskaming varve series. Erosional unconformities (or disconformities) below v1484 cause 51 and 47 varves to be 'missing' in both the Duparquet and Dufresnoy varve records, respectively. Error in the varve numbering relative to the Timiskaming varve series is estimated to be ±2 varves. Varve thickness data for each lake are listed in separate digital spreadsheet files (.xlsx and .csv formats). Mosaic posters depict CT-Scanner radiograph images of each set of lake cores and show the interpreted varve numbering and the between-coring-site correlations of the varve couplets.

Introduction

Between about 10,570 ± 200 and 8470 ± 200 ^{14}C cal BP, extensive glaciolacustrine sediments accumulated within a succession of proglacial lakes, known as Barlow, Barlow-Ojibway and Ojibway, which formed against the Laurentide Ice Sheet as it retreated northwards through northwestern Quebec-northeastern Ontario (Vincent and Hardy, 1979; Veillette, 1994; Dyke, 2004; Breckenridge et al., 2012). These sediments comprise the Greater and Lesser clay belts (Coleman 1909, 1922) and are well preserved within modern lake basins (see Breckenridge et al., 2012; Brooks, 2016c to 2016j, 2017; Brooks and Grenier, 2017a, 2017b; Grenier and Brooks 2017). Antevs (1925, 1928) interpreted the rhythmic couplets to be varves and compiled the Timiskamining varve series by correlating varve thickness patterns between locations in the region. Subsequent research has verified his regional varve correlations and identified ~2100 rhythmic couplets (Hughes, 1959; 1965; Paulen, 2001; Breckenridge et al., 2012; Brooks, 2016a).

As part of an investigation of the stratigraphy, distribution and triggering mechanism of subaqueous mass transport deposits (MTDs) buried within the sub-bottom of area lakes (see Brooks, 2016b, submitted), cores were recovered containing varved Lake Ojibway glaciolacustrine deposits[1] from study areas at Duparquet and Dufresnoy lakes, northwestern Quebec (Fig. 1). This report contains varve thickness data for the Duparquet and Dufresnoy varve records derived from these cores. Similar to Brooks (2016a), this report includes background information on the coring site locations at both lakes and summarizes the coring methodology and varve numbering interpretations. Varve thickness data for each lake record are listed in separate digital spreadsheet files (.xlsx and .csv formats) containing thicknesses measured along composite sequences through the recovered varve deposits. The report also includes CT-Scanner radiograph images of each set of lake cores that are laid out in a poster-sized figure showing the interpreted varve numbering and the between-coring-site correlations of the varve couplets. The recovered deposits are contemporary with and directly comparable to the Dasserat varve record, reported previously by Brooks (2017). The Duparquet and Dufresnoy varve records also augment those reported previously by Antevs (1925, 1928), Hughes (1959), Paulen (2001), Breckenridge et al. (2012), and Brooks (2016a).

Study areas

Dufresnoy (~14 km^2) and Duparquet (~50 km^2) lakes are located near Rouyn-Noranda, Quebec, and the Ontario-Quebec border, about 390 km northwest of Ottawa, Ontario (Fig. 1A). The lake basins have irregular shapes and bathymetries that reflect the undulating relief of the Canadian Shield bedrock and the varying thickness of late Quaternary sediments. Numerous bedrock islands are present in both lakes. The local surficial geology is mapped predominately as deep water glaciolacustrine sediments with minor outcrops of bedrock, pockets of glacial deposits, and wetlands (Veillette et al., 2010). Multiple stratigraphic levels of MTDs are interbedded within

[1] As there is no sedimentological or stratigraphical distinction between the glaciolacustrine deposits from the Barlow, Barlow-Ojibway, and Ojibway lake stages, for simplicity, all of the varves recovered in core from Duparquet and Dufresnoy lakes are considered to be glacial Lake Ojibway varves.

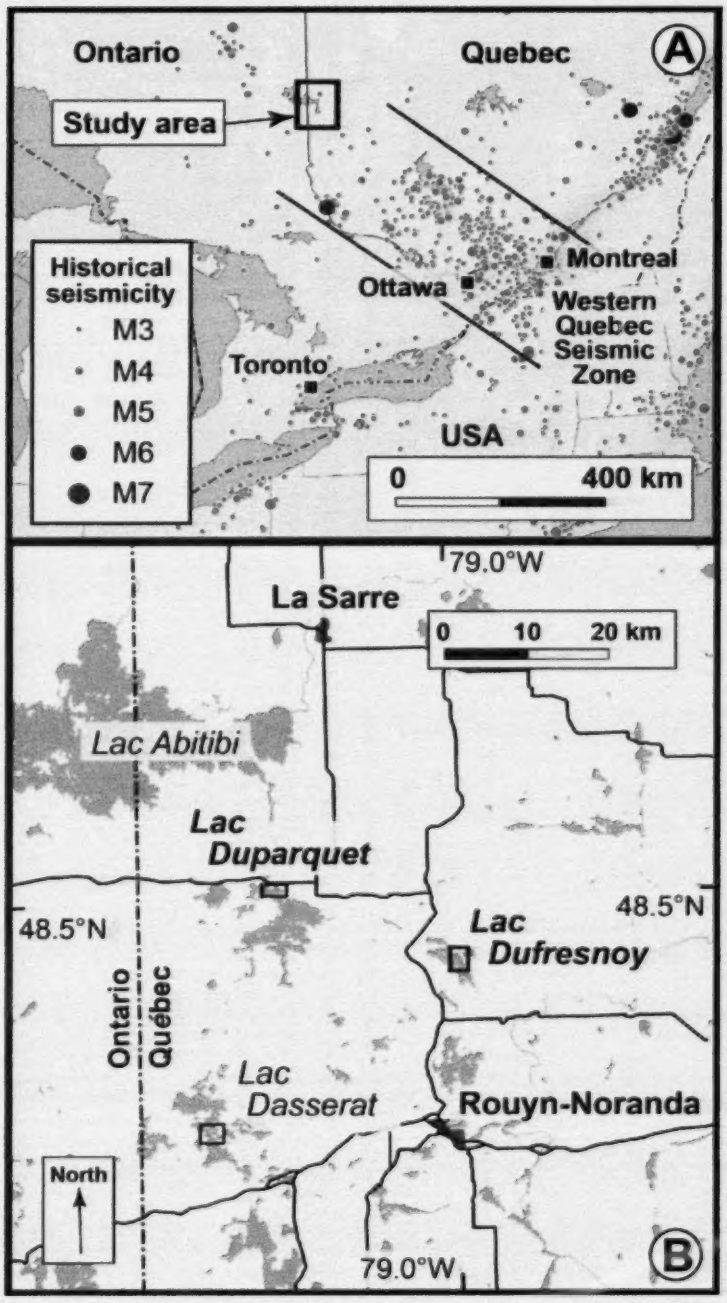

Fig. 1 Maps showing A) the general location of B) within northwestern Quebec, and B) the locations of the study areas at Duparquet and Dufresnoy lakes. Also shown is the location of the Lac Dasserat study area, which is mentioned in the text. Boxes in B) delineate the maps in Fig. 2 showing the coring locations at Duparquet and Dufresnoy lakes.

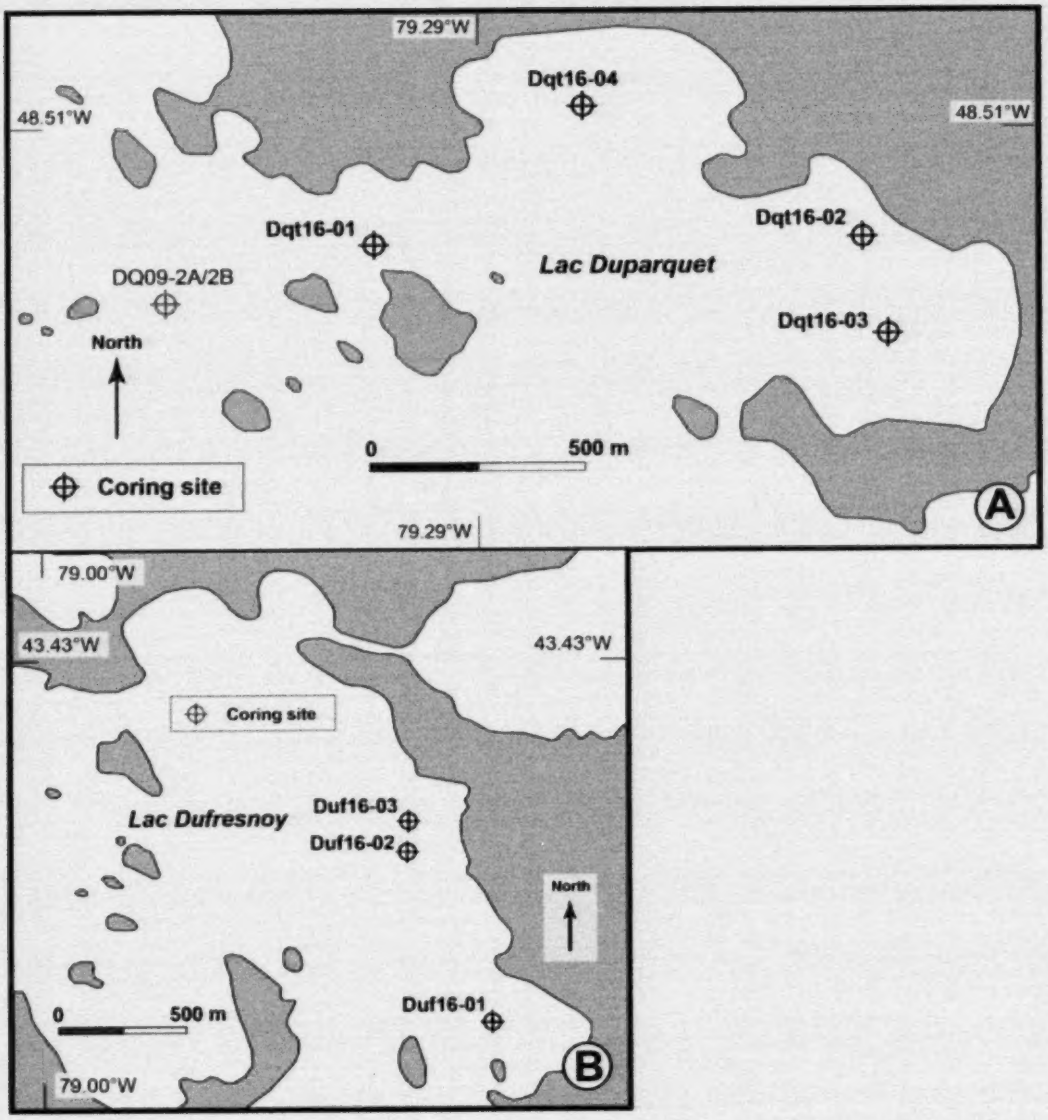

Fig. 2 Maps of the A) Duparquet and Dufresnoy B) study areas showing the locations of the coring sites. Also shown in A) is the location of coring site DQ09-2A/2B of Breckenridge et al. (2012) from which part of the varve thickness data originates (*see* Fig. 4).

glaciolacustrine deposits in both the Dufresnoy and Duparquet basins, as reported by Brooks (2016c, 2016d). Some of the MTDs are interpreted to be evidence of deglacial paleoearthquakes (Brooks, submitted).

Coring methodology

The coring sites at each lake were selected from sub-bottom acoustic profiles for the purpose of determining varve ages of MTDs that are interbedded within the glaciolacustrine deposits (see Brooks, submitted). Field work from an ice cover in March 2016 recovered cores at four and three locations within the Duparquet and Dufresnoy study areas, respectively (Fig. 2 and Table 1). The sites were located in the field using differentially-corrected GPS coordinates collected with a Novotel Smart-V1 antenna-receiver. Coring utilized a Livingston corer (Livingston, 1955) with 50.8 mm (O.D.) aluminum tubes that collected sections of core about 0.9 m long with 100% recovery. Each sampling site consisted of a pair of recovered cores, located about one metre apart with approximately 50% overlapping sampling segments. This process yielded a continuous, composite sample of the recovered deposits at each coring site. Immediately upon recovery, plastic caps and tape sealed the sampling tubes. The cores were stored carefully in the field to prevent freezing, and then transported to a temperature-controlled location.

Table 1 Coring locations at Dufresnoy and Duparquet lakes.

Lake	Core	Date cored	Latitude (°N)	Longitude (°W)	Water depth (m)	Depth of penetration (m)
Duparquet						
	LkDqt16-01	March 7, 2016	48.51000	-79.294983	2.91	3.95
	LkDqt16-02	March 8 and 10, 2016	48.50988	-79.279579	1.85	4.45
	LkDqt16-03	March 9 and 11, 2016	48.50783	-79.27887	1.77	8.95
	LkDqt16-04	March 11, 2016	48.51284	-79.288147	1.70	4.95
Dufresnoy						
	LkDuf16-01	March 12, 2016	48.419685	-78.980461	1.83	6.45
	LkDuf16-02	March 13, 2016	48.425995	-78.984764	1.93	4.95
	LkDuf16-03	March 16, 2016	48.427105	-78.984673	1.94	4.95

Core analysis at the Institut national de la recherche scientifique facility, Quebec City, Quebec, used a Siemens™ SOMATOM Definition AS+128 CT-Scanner to generate radiographs of the unsplit cores. This yielded tomodensitometry radiographs of the deposits in the X and Y longitudinal planes at a 1:1 resolution of 2.048 pixels/mm (52 ppi). Visual identification of distinctive couplets in the radiographs allowed the correlation of varves between the overlapping core segments for each coring site. Extending this process to the radiographs between different

coring sites produced a continuous, composite varve record through the recovered glaciolacustrine deposits for each lake.

Two people measured the thickness of each varve using 1:1 (or larger) scale radiograph images and the measurement tool in Adobe Illustrator™, with respect to a reference line placed perpendicular across each varve. The thickness results were then averaged, as recommended by Zolitschka et al. (2015). The varve measurements followed a composite sequence through the recovered deposits so that the thickness of each varve was measured just once (Tables 2 and 3). As much as possible, the composite sequence followed a track through well-preserved varves to avoid localized zones of microfaulting, cracks in the deposits, or sediment disturbance that is present commonly in the upper 0.1 m of each core segment. Later in the laboratory, the cores were split and logged. At the time of writing, the cores are archived in cold storage at the Geological Survey of Canada in Ottawa.

As shown in Fig. 3 and in detail on poster-sized figures in appendices A and B, the radiographs of the core segments for each lake are arranged vertically in relative stratigraphic position by core. Each core segment is depicted by a pair of X and Y longitudinal radiographs that extend through the centre axis of the deposits. The poster-sized figures show between-segment and between-coring-site correlations of the couplets and well as the interpreted numbers for each varve relative to the Timiskaming varve series.

Mass transport deposits

Although not the subject of this report, there are multiple stratigraphic occurrences of MTDs in the cores for each lake (see Brooks (submitted) for details). These deposits are highlighted by colour shading in Fig. 3, and appendices A and B. The MTDs deposits are composed of resedimented varves, but are readily recognized in the CT-Scan radiographs by the presence of tilted, deformed, contorted, convoluted, brecciated, and/or otherwise disturbed couplets that contrast markedly with the undisturbed, quasi-horizontal, over- and underlying beds/laminations. Brooks (submitted) mapped the stratigraphic occurrences of the MTDs in the study areas to define event horizons, each consisting of one or more separate MTDs. The varve ages he presented for these event horizons were interpreted from varve number of the first complete varve overlying a given MTD less one varve number.

Varve correlation to the Timiskaming varve series

Plots of varve thicknesses spanning 605 and 437 varve numbers along composite sequences through the Duparquet and Dufresnoy cores, respectively, are shown in Fig. 4. The varve numbering follows the Timiskaming varve series of Antevs (1925, 1928), and progresses sequentially from older to younger couplets. The plots are superimposed with the Dasserat (Brooks, 2016a), Duparquet (Breckenridge et al., 2012), and Timiskaming B7-B8a, A7, and F5-F6-F7-F8 varve record thickness data (Antevs, 1925, 1928; digital data from A. Breckenridge).

The post-v1484 numbering of the Duparquet and Dufresnoy records is interpreted based on an obvious thickening of the varve sequences that occurs beginning at v1528 (Fig. 4), a well-recognized, regionally distinctive marker bed within the glacial Lake Ojibway varves (Antevs, 1925, 1928; Hughes, 1959, 1965, Banerjee, 1973). The pre-v1484 numbering is interpreted by

Table 2 Varve numbers and associated cores and core segments comprising the Lac Duparquet composite sequence of measured varves.

Varve number range	Core, core segment
1685-1742	LkDuq2016-03, 00-100cm
1660-1684	LkDuq2016-03, 55-145cm
1611-1659	LkDuq2016-03, 105-195cm
1583-1610	LkDuq2016-03, 155-245cm
1564-1582	LkDuq2016-03, 205-295cm
1537-1563	LkDuq2016-03, 255-345cm
1526-1536	LkDuq2016-03, 305-395cm
1484-1525	LkDuq2016-03, 355-445cm
1427-1432	LkDuq2016-03, 405-495cm
1397-1426	LkDuq2016-03, 455-545cm
1385-1396	LkDuq2016-03, 505-595cm
1348-1384	LkDuq2016-04, 05-95cm
1318-1347	LkDuq2016-04, 55-145cm
1285-1317	LkDuq2016-03, 755-845cm
1254-1284	LkDuq2016-04, 155-245cm
1227-1253	LkDuq2016-04, 205-295cm
1212-1226	LkDuq2016-04, 255-345cm
1178-1211	LkDuq2016-04, 305-395cm
1137-1159	LkDuq2016-04, 405-495 cm

Table 3 Varve numbers and associated cores and core segments comprising the Lac Dufresnoy composite sequence of measured varves.

Varve number range	Core, core segment
1591-1625	LkDuf16-02, 05-95cm
1575-1590	LkDuf16-01, 05-95cm
1571-1574	LkDuf16-02, 05-95cm
1551-1570	LkDuf16-01, 05-95cm
1533-1550	LkDuf16-01, 55-145cm
1516-1532	LkDuf16-02, 105-195cm
1413-1515	LkDuf16-02, 155-245cm
1384-1412	LkDuf16-03, 05-95cm
1377-1381	LkDuf16-01, 255-345cm
1365-1376	LkDuf16-03, 55-145cm
1359-1364	LkDuf16-01, 305-395cm
1355-1358	LkDuf16-03, 55-145cm
1335-1354	LkDuf16-01, 305-395cm
1314-1334	LkDuf16-01, 355-445cm
1292-1313	LkDuf16-03, 205-295cm
1289-1291	LkDuf16-03, 155-245cm
1267-1288	LkDuf16-03, 205-295cm
1223-1266	LkDuf16-03, 255-345cm
1203-1222	LkDuf16-03, 305-395cm
1189-1202	LkDuf16-03, 355-445cm

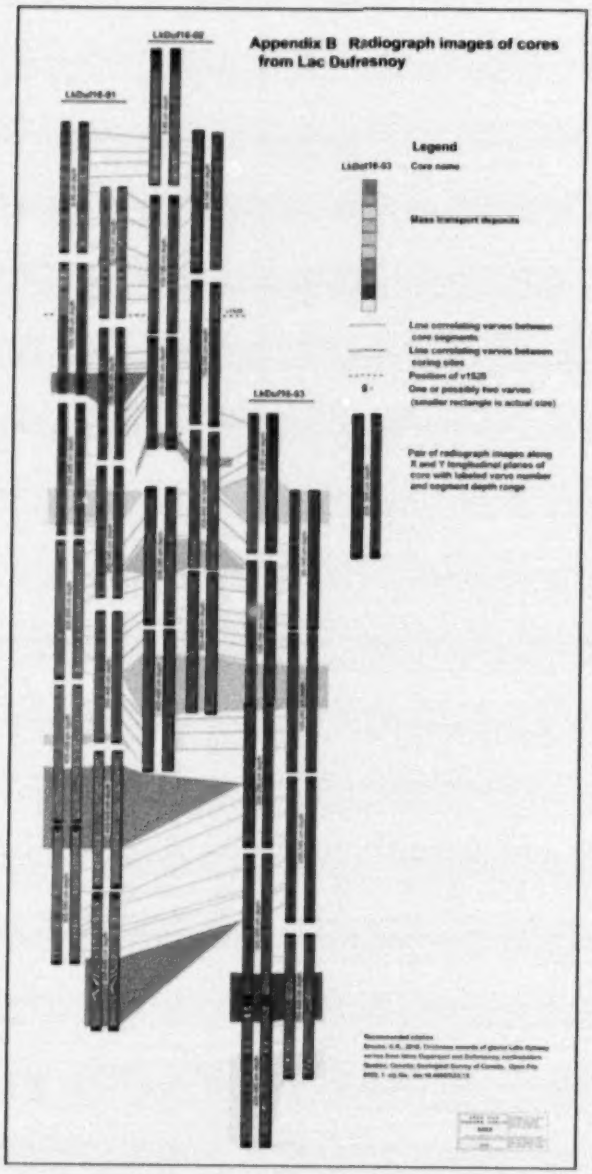

Fig. 3 Small-scale version of one of the two core mosaic diagrams, showing the general lay-out of the radiographs; refer to the poster-sized version in the appendices to see specific details. In the figure, the radiographs are arranged vertically in relative stratigraphic position under the core headings. Each core segment is represented by a pair of radiographs showing the deposits along the central longitudinal X and Y planes. Correlation lines link selected varves between core segments (orange lines) and between the coring sites (red lines). Selected varves are labeled by Timiskaming series varve number. A dashed line labeled 'v1528' marks a distinctive thickening of the varves that occurs regionally within the Lake Ojibway glaciolacustrine deposits. Stratigraphic occurrences of mass transport deposits within the cores are represented by the coloured areas.

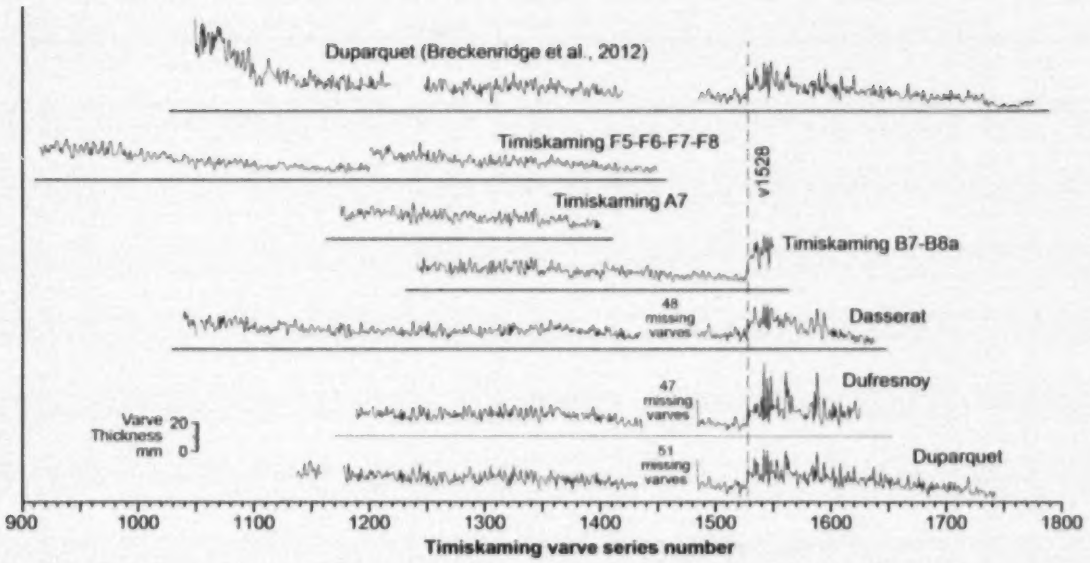

Fig. 4 Plots of varve thickness versus Timiskaming varve series numbering for the Duparquet and Dufresnoy varve records; varve numbering increases from older to younger varves. Also shown are plots of the Dasserat (Brooks, 2016a), Duparquet (Breckenridge et al., 2012) and, Timiskaming A7, B7-B8a, and F5-F6-F-7-F8 varve records (Antevs, 1925, 1928; data from A. Breckenridge). Note, the obvious increase in varve thickness occurring at v1528, which is a distinctive, regional marker bed, as mentioned in the text.

visually matching the thickness patterns to the Duparquet (Breckenridge et al., 2012) and Dasserat (Brooks, 2016a) plots. Not shown on the Duparquet plot are 27 thin varves situated at the top of the glaciolacustrine deposits that are separated from the older varves by a zone, 0.11 m thick, of indistinct, unmeasurable couplets.

The resulting Duparquet and Dufresnoy varve records span v1137-v1742 and v1189-v1625, respectively. The correlations to the Timiskaming varve series reveal major unconformities (or disconformities) of 47 and 51 missing varves immediately below v1484 in both records, as is similar to the Dasserat varve data (Fig. 4). The varve thickness data and varve numbering relative to the Timiskaming varve series are listed in spreadsheets in .xlsx and .csv formats in appendices C (Duparquet) and D (Dufresnoy).

Statistics from Antevs varve correlation software (v.1.3.6; Vollmer, 2016) between the Duparquet and Dufresnoy records with the Dasserat and Timiskaming A7, B7-B8a, and F5-F6-F-7-F8 varve records are listed in Table 4. Correlating each of the pre- and post-v1484 portions of the Duparquet and Dufresnoy data separately yielded substantially better correlations to the other records than the full varve records (not shown). The v1137-v1432 and v1484-v1742 portions of the Duparquet record have Pearson's r values of 0.497-0.750 and 0.690-0.839, respectively. All of the offsets are zero, except for B7-B8a, which is a spurious 354. These correlation data support the interpreted Duparquet varve numbering in Fig. 4.

The Dufresnoy v1484-v1625 range has Pearson's r values are 0.685 and 0.722 with offsets of zero (Table 4) that support the post-v1484 varve numbering in Fig. 4. For the v1189-v1436 range, Pearson's r values are 0.450-0.588 with an offset of zero for B7-B8a, but offsets of one varve year for the Dasserat, A7 and F5-F6-F-7-F8 records. Although present in three of the four comparisons (Table 3), this slight offset is not applied to the v1189-v1436 numbering because it produces a one-varve displacement to many distinctive varves between the Dufresnoy, Duparquet and Dasserat records that would otherwise be aligned. This offset is deemed insignificant and the correlation statistics are considered to support the v1189-v1436 range of varve numbering in Fig. 4.

Similar to Brooks (2016a), the error in the varve numbering between the Duparquet and Dufresnoy records with the Timiskaming A7, B7-B8a, and F5-F6-F7-F8 records is considered to be ±2 varves, as assessed from localized one to two varve displacements in distinctive couplets. This displacement reflects missing or false varve(s) between the records, but tends to be self-cancelling along the varve sequences (Lamoureux, 2001). Between the Dufresnoy, Duparquet and Dasserat cores, however, the location of false and missing varves in one record was assessed by comparing the numbering assigned to specific distinctive varves on the CT-scan imagery with that from the other two lakes. This allowed the varve numbering to be made consistent between these three lake records, reducing the numbering error to zero. The ±2 error still applies between the varve numbering of these three lakes to those of the Timiskaming varve series, for which the original data only exist in graphical (or digitized graphical) form (e.g., Fig. 4).

Although falling outside the composite varve sequence, there are two short sections of uncertain varve numbering in the cores from both lakes. In core Dqt16-03, 705-795 cm, from Lac Duparquet (Appendix A), v1323 to v1327 is a short couplet sequence interbedded between two mass transport deposits. The assigned numbering is based on the correlation of the distinctly thick v1325 and v1327 couplets to the sequences in the other Duparquet cores, but is not

Table 4 Varve correlation statistics from Antevs 1.3.6 (Vollmer, 2016) for the Duparquet and Dufresnoy varve records compared to the Dasserat and selected Timiskaming varve series records. The statistics were obtained using the default settings of Antevs 1.3.6, which applied detrending using a 16-term Fournier curve and then filtering that averaged the three nearest data points.

Varve range	Varve record	r [a]	z [b]	n [c]	t [d]	Offset
Duparquet v1137-v1432						
	Dasserat	0.666	6.029	297	11.464	0
	Timiskaming A7	0.612	5.209	226	9.187	0
	Timiskaming B7-B8a	0.497	3.965	60	3.818	354
	Timiskaming F5-F6-F7-F8	0.750	7.173	297	12.904	0
Duparquet v1484-1742						
	Dasserat [e]	0.690	5.865	154	8.540	0
	Timiskaming B7-B8a [e]	0.839	5.414	67	6.815	0
Dufresnoy v1189-1436						
	Dasserat	0.548	4.789	245	8.560	1
	Timiskaming A7	0.504	4.116	211	7.308	1
	Timiskaming B7-B8a	0.450	3.606	194	6.245	0
	Timiskaming F5-F6-F7-F8	0.588	5.274	245	9.181	1
Dufresnoy v1484-1625						
	Dasserat [e]	0.685	5.078	142	8.129	0
	Timiskaming B7-B8a [e]	0.722	4.353	67	5.863	0

[a] Pearson's r value.
[b] z-score.
[c] Number of overlapping varves.
[d] Significance measurement.
[e] Record includes v1528.

unequivocal. In Lac Dufresnoy cores (Appendix B), the varves at the bottom of core LkDuf16-02, 205-295 cm, could not be matched to those at the top of LkDuf16-02, 255-245 cm, because of localized varve disruption in the shallower core. Also, core LkDuf16-02, 205-295 cm was short, limiting the overlap between the two cores. This problem is localized as marked in Appendix B and does not affect the composite varve sequence which is defined using cores LkDuf16-01 and -03 (Table 3).

There are 12 and 33 couplets in the Duparquet and Dufresnoy cores, respectively, that are flagged with small red rectangles on the core radiograph (appendices A and B). These could be interpreted as representing one or possibly two varves and represent 2% and 9%, of the 537 (Duparquet) and 387 (Dufresnoy) long varve sequences. An uncertain varve usually is significantly thinner than the immediately over- and underlying varves and appears more or less as a couplet within a couplet. Within sequences of overlapping varves between the coring sites, an uncertain varve commonly is present in one core, but absent in the equivalent location in another core. This, together with the much thinner couplet size, suggests that these are 'false varves'. How such varves are interpreted in the two varve records can be discerned readily from the varve numbering annotated on the core mosaics (appendices A and B).

Duparquet and Dufresnoy varve records

The purpose of the coring was to determine varve ages for the MTD of interest in the study areas (see Brooks, submitted), hence the presented records do not span the full sequence of varves preserved in Duparquet and Dufresnoy lakes. The oldest recognized varve in Lac Duparquet is v1049, identified by Breckenridge et al. (2012), which is approximately 90 varve years older than the oldest varve (v1137) reported in this study. The youngest varve identified in the present study is v1742, which is close, but moderately older than v1776, the youngest varve in Lac Duparquet, recognized by Breckenridge et al. (2012).

The varve sequence in Lac Dufresnoy probably begins between v900 and v1000, as estimated from Breckenridge et al. (2012, their Fig. 7). This implies that there are about 90 to 190 unrecovered varves in the sub-bottom that are older than v1189, the oldest recognized in this study. The youngest varve (v1625) in the presented record probably is 100-150 varves older than the end of varve sedimentation. This range is inferred from the thickness difference in sub-bottom profile returns between the top of the recovered sediments at the core site Duf16-02 and locations elsewhere containing the glaciolacustrine to lacustrine deposits.

In both varve records, the v1484 rhythmite is markedly thicker than the immediately overlying varves (Fig. 4). This thickness likely reflects sediment re-suspended into the glacial Lake Ojibway water column in vyr1483 by widespread mass movements that occurred regional, mostly likely by a paleoearthquake (see Brooks, submitted). MTDs associated with these mass movements immediately underlie v1483 in cores LkDqt16-03 and LkDuf16-01 (see appendices A and B). The v1484 rhythmite is interpreted to represent an annual layer, as it otherwise resembles the immediately overlying varves.

Conclusions

The Duparquet and Dufresnoy varve records contain 537 and 387 measured couplet thicknesses, respectively, along composite sequences of varves. The couplets span varve numbers 1137 to

1742 (Duparquet) and 1189 to 1625 (Dufresnoy) with respect to the Timiskaming varve series. Erosional unconformities (or disconformities) below v1484 cause 51 and 47 varves to be 'missing' in the Duparquet and Dufresnoy records.

Error in the numbering of the Duparquet and Dufresnoy varve records relative to the Timiskaming varve series records is estimated to be ±2 varves. There are 12 and 33 couplets in the Duparquet and Dufresnoy radiographs that are flagged as representing one or possibly two varves.

Varve 1528 is present within both the Duparquet and Dufresnoy varve records. This is a distinctive varve that corresponds to a marked increase in varve thickness and occurs regionally within the Lake Ojibway glaciolacustrine deposits.

The recovered deposits are contemporary with and directly comparable to the Dasserat varve record, reported previously by Brooks (2017).

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